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A Review of the Effect of Electric Discharge Machining on the Surface Integrity of Metallic Parts

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ABSTRACT

In Electric Discharge Machining (EDM), after each electric discharge, a small portion of the molten pool is removed and the residue re-solidifies on the surface in the form of layer. This re-solidified layer has different microstructure and metallurgical properties than the parent material. Many investigations have been carried out on EDM of different materials to evaluate the influence of electrical parameters, dielectric type, electrode material and discharge gap on the Material Removal Rate (MRR), tool wear rate and surface integrity (surface roughness, cracks, residual stresses and white layer formation). Voltage, pulse current, pulse on-time, pulse off-time and polarity are electric parameters that control discharge energy as well as heating and cooling times. It has been observed that high discharge energy gives high surface roughness, high MRR and high residual stresses. A detailed literature review comprising effects of different parameters on surface conditions like metallurgical characteristics, surface roughness, surface hardness and distribution of residual stresses, is presented here.

1. Introduction

Electrical Discharge Machining (EDM) is a thermo-electrical material removal process that is used for the machining of difficult-to-cut materials and complex geometries [1]. Due to recent developments in control system, EDM is getting acceptability in industrial usage along with conventional machining processes. EDM provides improved productivity, precision and accuracy in machining of complex geometries [2]. Commercially, EDM has approximately 7% of sales of machine tools globally [3]. Use of EDM is inevitable in aerospace industry because of its relatively higher precision and accuracy for machining of intricate shapes. Die-sinking EDM is mostly used for the preparation of molds and micro-machining applications [4] whereas wire-cut EDM is for precise cutting operation.

EDM processing is based on localized electric sparks between electrode and work-piece which causes melting or evaporation of the material [5].The spark generators creates electric charges on the surfaces of tool electrode and work-piece in the dielectric liquid. Dielectric liquid is polarized and molecules start to arrange between closest surfaces of tool and work-piece electrodes until ionization takes place. Electrons and ions collide on the electrodes and their kinetic energy is converted into heat energy [6]. Electric discharge creates high temperature, up to 10000 ºC, due to which, work-piece material melts and/or evaporates [1]. At the end of each discharge, violent expulsion of super-heated material of both electrodes occurs in the dielectric liquid and then surfaces cool instantaneously [6]. Dielectric liquid is used to remove this molten material in the form of debris and small hemi-spherical cavities are formed on the surface that are termed as 'craters' [7]. Only about 15% of the molten material can be removed and the remaining material re-solidifies on the surface [8] in the form of a layer that is called "white layer" (WL) or "recast layer" (RL) [9]. The surface generated by ED machining is unreflective and non-directional and the size of the spherical shaped crater is dependent on the melting point of the material and electrical parameters [10].

Thermal stresses are also generated on the surface after rapid cooling of the molten material which is termed as "residual stresses". These residual stresses, if greater than the yield strength of the material, result in cracks/micro cracks on the surface/subsurface of the machined parts [9]. Upper surface becomes harder and brittle after these high temperature thermal deformations. Below the WL there is an annealed region which is known as the "Heat Affected Zone" (HAZ). Micro cracks that originate from WL often penetrate into HAZ. but most of the core material remains unaffected [9].

Surface conditions play a key role in deciding the fatigue life of components, as cracks usually initiate from the surface from the existence of maximum bending and torsional stresses on the outer surfaces. EDM machining alters the surface in two ways; 1) geometric defects in the form of stress concentration by machine like scratches and 2) metallurgical alterations in the surface and subsurface layers. Surface integrity is measured in the form of surface geometry and physical properties like hardness, RS and microstructure [11].

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Endurance limit is based on the particular machining process and operation procedure [12]. Fatigue failure is considered as a two-step procedure, i.e. crack initiation and propagation, which is limited to only crack propagation step due to pre-existing cracks in white layer. Seventy percent of the total fatigue life is consumed in crack initiation for high stresses whereas this value increases to 90% for low stresses [13]. Therefore, it is obvious that surface conditions are important for total service life of the material.

In this work, a detailed review of the effect of EDM machining on the surface integrity and fatigue behaviour of different materials is presented. Effect of EDM on the surface roughness (SR), micro-hardness, surface topography and RS have been emphasized in the perspective of fatigue life response.

2. Evaluation of surface integrity after EDM

The surface produced after EDM is generally characterized for white layer formation, crack generation, variation in hardness and residual effects in the material:

2.1 White Layer Formation

The surface that is melted by the heat, generated from electric sparks, partially removed and after rapid quenching re-solidifies and remains stuck on the surface is called the white layer (WL) or recast layer (RL) [9]. The micro-structural observations reveal that WL may have many sub layers of different structure and phases depending on discharge energy [14]. WL has been studied by many researchers after EDM for different materials.

Shabgard et al. [9] found that Pulse on-time has greater influence on white layer thickness (WLT) and the depth of HAZ as compared to pulse current during a parametric study in order to achieve good surface integrity of AISI H13 tool steel using copper as tool electrode [9]. Whereas, Urooj et al. [15] determined that WLT of Al 6061-T6 increases with the current initially but after certain value, WLT starts to decrease because of intense crack formation that is easily flushed away by kerosene as dielectric liquid. After each discharge, cooling starts from the surface, transfers vertically inward and solidification occurs in a dendritic structure [16]. Mannan et al. [8] reported that ED machining effect is observed only in the three upper layers in tool steel i.e. WL, heat affected layer and transition layer. Micro-structure of bulk material remained unaffected. Gostimirovic et al. [17] also determined that thickness of WL increases with discharge energy. They reported that four distinct layers were observed in the EDM machined surface of Manganese-Vanadium tool steel with copper electrode, which are, 1) melted layer: sludge of melted particles, 2) hardened layer: consists of martensite, residual austenite and cementite, 3) interface layer: consists of martensitic-austenitic grid and cementite, where the fraction of austenite reduces with the distance from the tempered layer, and 4) tempered layer: tempered martensite and cementite that converts into simple microstructure of martensite with fine globular cementite [17].

Thickness of WL and cracks density in WL are inversely related to the thermal conductivity of the material and directly proportional to the thickness of the work-piece [18]. As material with high thermal conductivity allows thermal energy to dissipate into surrounding bulk material that decreases the temperature intensity in the localized area, due to which, pool of molten material decreases. White layer thickness influences microstructure and three broad categories of WL are identified as 1) multilayer WL composed of overlapping layers of complex dendritic microstructure with thickness above 10 µm, 2) single layer WL with thickness between 10-20 µm and comprised of three sub layer with top columnar layer, middle sub layer is complex dendritic interlocking and bottom sub layer is composed of perpendicular dendrites to the surface, and 3) featureless WL which is un-etchable is seen when the energy level is low [18]. Ghanem et. al. [19] reported that WL after EDM of tool steel comprised of three consecutive layers. Upper layer is of dendritic nature, medium layer is quenched layer and third layer is transition zone. Hasçalýk and Çaydaş [20] performed experimental investigation of wire EDM machining of AISI D5 tool steel. Four distinct layers were observed after EDM machining. The outer most layer was debris layer followed by WL, annealed layer and the parent material. WL is the hardest layer, whereas, annealed layer is softer than parent material.

Jha et al. [21] studied the effect of EDM machining on 15-5 PH stainless steel used in aerospace applications. They found that the thickness of WL ranges from 50-70µm. WL have micro cracks that often terminate before bulk material but at some locations cracks are seen penetrating from WL to the parent metal. It was noted that these cracks can be avoided by increasing pulse current value and reducing pulse on time value. Thickness of WL also depends on the type of dielectric fluid, electrode size and machining parameters. Ekmekci et al. [6] discussed the surface integrity of plastic mold steel generated by electric discharge machining. The resulting surface has second phase particles that more round in shape than the carbides in parent material. It was observed that there is thermally affected layer under WL that has tempered microstructure. This layer is enriched by carbon contents that may be absorbed from dielectric liquid or tool electrode. Lower layer has slightly lower hardness than the hardness of WL. Thickness of Heat Affected Zone (HAZ) is proportional to the discharge energy. For rough ED machining conditions, cleavage and boundary cracks were seen that extended into the underlying material. The bulk material that was below the HAZ was unaffected by EDM machining.

2.2 Surface Cracks

The re-solidified layer formed on the surface of the material after electric discharge machining contains cracks for steel [8, 22, 23], aluminum alloy [15] and Titanium alloy [24]. Cracks initiate from the surface and penetrate the WL mostly terminating within the WL and rarely extend into the base material. These cracks are very small in size and are termed as “micro-cracks” with density is proportional to pulse on time. Density of cracks is independent of the pulse current for lower pulse on time values, but, for high pulse on time density of cracks is inversely related to the pulse current in case of D2 and H11 tool steel [25].

For same machining conditions, the susceptibility of material to cracking and white layer thickness is inversely related to the thermal conductivity of tool steel material. Cracks are often observed in the structure which is not moving in columnar pattern perpendicular to the base surface. Multi-layer type WL is more prone to cracking, fewer cracks in single layer WL and very rare cracks occur in featureless WL [18].

Lee et al. [26] determined the effects of EDM process parameters on tungsten carbide. It was found that damaged layer developed on the surface of the material, which contains higher quantity of micro grains for ED machined surface as compared to the original material. This layer has clusters of micro cracks that vary with current and pulse time. Length, depth and density of these cracks are observed to increase with increase of current and pulse time. At lower values of current and pulse time, cracks completely vanish.

About such small cracks, Gyansah and Ansah [27] suggested that these small cracks should not be ignored because these could be as detrimental to cause complete failure of the structure. Surface cracks produced after EDM machining of pure iron, 0.15C steel and 0.5C steel were also studied by Lee at al. [28]. The susceptibility of material to cracking was attributed to the recast layer hardness [28] and thermal conductivity [25].

Mehmood et al. [29] determined the effect of impulse current on the surface morphology of AA 2024 T6. For the discharge currents of 3-6 A, no cracks were seen on the surface and nor across the surface. For the discharge currents of 9 and 12 A, short cracks appeared on the surface as well as into the machined surface. Despite this fact, Rao et al. [30] reported that no micro cracks were seen for all current levels for the same material. Rebelo et al. [31] evaluated surface quality after EDM machining of martensite steel and found that pulse energy significantly influenced the Crater size, cracks density and WLT. The “WLT” was the function of product of peak current and pulse duration. Moreover no single parameter can determine WLT completely. Roughness and carbon contents in WL are dependent on pulse energy as well as the materials of both tool and work piece.

Ekmekci et al. [6] presented a detailed discussion regarding surface quality after EDM machining by using copper and graphite electrodes as tool materials and kerosene and de-ionized water as dielectrics. EDM generated craters of circular shape which were found independent of tool material, dielectric liquid and all other parameters. High discharge energy gives big pool of molten material that result in the formation of globules and cracks in WL by rapid and uneven solidification of the molten material. Hardness of WL is more than the parent material and hardness of heat affected tempered layer is less than bulk material. Carbon collected from dielectric liquid and tool material was deposited along the lips of craters. Carbon contents in WL were produced by pyrolysis process of Hydrocarbon based dielectric liquids. A Larger number of cracks were produced at low current and high pulse duration settings (8A and 800 µs). But, for high discharge energy setting, i.e., high current and high pulse duration (16A and 800 µs) crack density decreased and close loop pitting appeared along the surface cracks. Maximum crack density was found for maximum pulse duration and minimum pulse current.

2.3 Surface Hardness

Below the melted and re-solidified layer is a re-hardened layer and then tempered layer comes in case of EDM of tool steel [32]. The temperature rises above the hardening (austenitizing) temperature. Hard and brittle martensite is formed in re-hardened layer. In the tempered layer the material is heated up to hardening temperature due to which material is tempered back [33]. The hardness of the tempered layer is less than hardness of the parent material. The effect of temperature reduces gradually after tempered layer and completely disappears in the core material, due to which, hardness starts to increase after tempered layer until the hardness of the core material is reached [34]. WL has refined microstructure as compared to the parent material, therefore, WL have 45% higher hardness than bulk material [35]. Hardness of the material directly affects service life of the material [36].

Jabbaripour et al. [37] differentiated the layers formed after EDM of Ti–6Al–4V by their microstructure and mechanical properties (hardness and ductility etc.) and found that surface hardness is directly proportional to the applied discharge energy. Ekmekci et al. [38] reported that white layer is harder than the core material. Hardness value drops dramatically till some certain depth in HAZ lower than that of core material and no correlation is found between the affected layer and hardness depth. This observation was verified by Gostimirovic et al. [17] for ED machining of Manganese-Vanadium tool steel with copper electrode. Kruth et al. [39] studied the WL hardness of Mold Steel Impax, Carbon Steel C35 and Pure Iron Armco after ED machining in different types of dielectric media. They found that oil dielectrics produce greater hardness because iron carbides are formed in the surface by absorbing the carbon components from oil based dielectric during ED machining. For water as dielectric liquid, de-carbonization of white layer occurs and hardness decreases as compared with the parent material. Ghanem et al. [19] compared surface integrity after EDM and milling process for tool steel and found that Carbon contents increased in the affected layer due to decomposition of dielectric liquid in EDM whereas no changes in composition were observed in case of milling. EDM generated WL have hardness four times that of the bulk material whereas milled surface have small increase in hardness as compared to core material. Lee and Li [26] determined the effects of EDM process parameters on tungsten carbide and found that ED machined surfaces have same hardness as the hardness of surfaces that are not ED machined for all EDM conditions. Li et al. [40] studied the surface integrity for Inconel 718 after wire-EDM and found that WL formed was not as hard as the bulk material because this material does not have enough carbon that make WL harder as mostly happens in the case of steel. Ghanem et al. [41] found that the EDMed surface hardness is three times greater than the hardness of the bulk material when evaluating the influence of steel types on the surface integrity after ED machining. Jeelani and Collin [42] observed that the hardness of WL after ED machining of Inconel 718 is greater than the parent material, due to which, the surface becomes brittle which resulted in reduced fatigue life. But, in contrast, for the same material, Newton et al. [43] found a decrease in hardness of WL as compared to the parent material.

2.4 Residual Stresses

Residual stresses (RS) are self-equilibrating type of stresses that can exist in the material without any applied load. EDM generates thermally induced RS in the WL by inhomogeneous plastic deformations. RS can be measured by both destructive and non-destructive methods. Destructive methods are based on relaxation of stresses after layer removal by chemical etching, drilling and sectioning. Non-destructive methods are based on the measurement of atomic displacements by X-ray diffraction and measuring velocities of ultrasonic waves passing through the material [44]. For small roughness values, RS exhibits dominant influence on surface integrity [45]. Mehmood et al. [46] determined the effect of EDM on and below the surface of AA 2014 T6. The effect of discharge current on the magnitude of residual stresses is clearly seen and concluded that these are of tensile nature irrespective of the discharge current level used during EDM machining.

Navas et al. [47] made a comparative study of wire EDM machining with production grinding and hard turning of AISI-01 tool steel. They classified RS into two type: (1) Macro residual stresses and (2) Micro residual stresses. Macro residual stresses exist among grains and they are comparatively easier to measure, whereas, micro stresses exist around defects or flaws and are difficult to determine by traditional methods. Three types of stress distributions were discussed by Parrish [48]. Type-I represents stresses developed after machining. Type-II is the most undesirable; plastic deformation at the surface which generates compressive stresses and huge amount of heat under this layer producing high tensile stresses. Type-III gives the pattern obtained by gentle machining and EDM generates tensile stresses at the surface, whose value increases in depth and reaches a maximum and then starts to disappear gradually. This is close to the Type-II trend that is the worst stress distribution. This stress distribution may cause crack initiation at early stage and fast crack propagation. Finish parameter setting (low discharge energy) after rough machining causes decrease in residual tensile stresses [47].

Ekmekci et al. [49] developed a semi empirical model for the determination of RS by removing EDMed layers by Electro chemical machining of plastic mold steel with de-ionized water as dielectric liquid. They found that RS depend on discharge energy and are independent of the pulse duration and current values. It was also observed that RS are tensile in nature which increase in the depth and reach their peak value within HAZ and then fall rapidly to low value of compressive RS. The intensity of surface cracks is independent of discharge energy and peak value of tensile RS is close to the ultimate tensile strength of the material. Residual stresses cause cracks on the hump of WL [18]. Lee at al. [50] measured RS in EDMed carbon steel by the hole-drilling strain gauge method. RS were realized to be related to WLT, which are greater at higher values of pulse current and pulse on time.

Mehmood et al. [51] studied the effect of pulse current during EDM on the micro-hardness of Aluminum alloy and it was found pulse current is inversely related to surface hardness. Das et al. [52] predicted the crater size/shape and RS with depth successfully for single pulse discharge. Production grinding process produces compressive stresses at the surface but high tensile peak occurs below the surface. Conventional hard turning generates tensile RS at the surface but high compressive RS are below 10μm [47].

3. Discussion and Future Trends

In this paper, effect of electrical parameters, dielectric medium, gap between electrode and work-piece and electrode material on characteristics such as white layer appearance, cracks, hardness and residual stresses of electric discharge machined surfaces are presented. Various investigations carried out in the last two decades are summarized in Table 1.

EDM produces a re-solidified layer on the surface which is termed as White Layer (WL). This layer has different properties as compared to the parent material. This layer is brittle, hard, has very refined microstructure and excellent adhesion with base material. Below this white layer is the ‘Heat Affected Zone (HAZ), which is a tempered layer having lower hardness even as compared to the parent material. Below this HAZ, bulk material occur which remains unaffected. Rapid cooling of molten

Table 1: Different investigations carried on various metals to study the effect of EDM on surface integrity parameters.

Year	Authors	Material	Response variables	Influencing parameters	Remarks
2011	Shabgard et al. [9]	AISI H13 tool steel	WLT and depth of HAZ	Current/Pulse-on time	Optimum process parameters are investigated for desired surface integrity
2014	Urooj et al. [15]	Al 6061-T6.	WLT and composition	Current	MRR and surface morphology is investigated with respect to discharge current.
2010	Jha et al. [21]	15-5 PH stainless steel.	WLT	Dielectric fluid, electrode size and machining parameters	The thickness of WL ranges from50-70µm
2005	Ramasawmy et al. [16]	Tool steel (0.38% C, 16% Cr)	WLT, density of cracks and micro-hardness		Higher thermal conductivity of material is causing surface cracks.
1998	Rebelo et. al [31]	Martensite Steel	Crater size, crack density and WLT	Pulse energy	Dependence of residual stresses and surface roughness on process parameters is studied.
2004	Hasçalýk et. al [20]	AISI D5 tool steel	White layer (WL)	Pulse duration and open circuit voltage	Outermost is the debris layer, second layer is WL, third layer is annealed layer, and fourth is the parent material
2012	Jabbaripour et al. [37]	Ti-6Al-4V	MRR and Tool Wear Rate (TWR)	Current/Pulse-on time	Density of cracks are inversely related to the thermal conductivity of the material and directly proportional to the thickness of the work-piece.
2009	Tai and Lu [53]	SKD 11 tool steel	Surface cracks	Current/Pulse-on time	High current and low pulse-on time suppress formation of cracks.
2010	Jha et al. [21]	15-5 PH stainless steel.	Surface cracks	Current/Pulse-on time	Cracks can be avoided by increasing pulse current value and reducing pulse on time value
2003	Lee and Li [26]	Tungsten carbide	Surface cracks	Current/Pulse-on time	WLT and cracks increase with pulse current and pulse-on time.
2010	Lai et al. [5]	Nickle based super alloy	Fatigue life	Grain size	EDM deteriorate fatigue strength of nano-crystalline Nickel but do not affect coarse grains.
2003	Lee and Tai. [25]	D2 and H13 tool steel	Crack density	EDM parameters	Maximum crack density exists at the lower values of pulse current and higher pulse on-time
2010	Gyansah et al. [27]	Steel	Cracks	Fatigue strength	Small cracks should not be ignored because these could be as detrimental as large cracks to cause complete failure of the whole structure
1992	Lee at al. [28]	pure iron, 0.15C steel and 0.5C steel	Cracks in white layer	Process parameters	The crack susceptibility was attributed to the recast layer hardness and thermal conductivity
2012	McKelvey and Fatemi [36]	forged steel	Fatigue performance	Hardness	Hardness is found proportional to fatigue strength
2005	Ekmekci et. al [38]	Plastic Mold Steel	Hardness, RS	Current/Pulse-on time	Tensile residual stresses develop below the EDMed surface.
2013	Li et al. [40]	Inconel 718	Hardness	Discharge energy	Reduction in WL hardness occurred.
1995	Kruth et al.[39]	Mold Steel	Hardness	Dielectric liquid	Carbon is transferred from oil into white layer.
2003	Lee and Li [26]	tungsten carbide	Hardness	Current/Pulse-on time	Density of micro cracks increased with pulse current and pulse-on time.
2003	Ghanem et al. [41]	steel types	Hardness	Current	Near surface hardening due to carbon enrichment depends strongly on the initial structure (BCC or FCC).
1988	Jeelani and Collins [42]	Steel	Fatigue life	Cutting speed	Fatigue lives of the machined specimens decreased slightly, but remained unchanged with variations in cutting speed.

Year	Authors	Material	Response variables	Influencing parameters	Remarks
2009	Newton et. al. [43]	Inconel 718	Hardness, white layer	Current, Pulse on-time	In white layer, hardness and elastic modulus are lower than bulk material.
2004	Lee at al. [50]	carbon steel	Residual stresses	WLT	Residual stresses increase at higher values of pulse current and pulse-on time.
2008	Garc´ıaNavas et al. [47]	AISI-01 tool steel	Residual stresses, hardness	Comparison with turning and grinding	EDM is the most detrimental to surface integrity and fatigue performance.
2006	Ekmekci et al. [38, 49]	plastic mold steel	Residual Stresses	Discharge energy	Residual Stresses are independent of the pulse duration and current
2004	Leão and Pashby [3]	Review article	Machining characteristics	Dielectric liquids	Each dielectric liquid had its own characteristics and advantages
2014	Zhang et al. [54]	Mold steel 8407	Crater size and shape	Dielectric liquids	Material removal efficiency of liquid dielectrics is found better than gaseous dielectrics
2011	Zhang et al. [55]	Steel alloy	Surface characteristics	W/O emulsion	The RL that is developed by using W/O emulsion have highest hardness, thickness and SR
1999	Chen et al. [56]	on Ti-6Al-4V	Surface characteristics	Kerosene and distilled water as dielectric	Distilled water has greater MRR and lower tool wear ratio than kerosene
2012	Govindan et al. [57]	SS 304	Surface characteristics	Air as the dielectric	Liquid dielectric produces about 1.5 to 6 times the average crack length as compared to dry EDM.
1995	Wong et al. [58]	Steel alloys	Surface cracks and WLT	Flushing pressure	There is optimal flushing rate.
2009	Boujelbene et al. [59]	Die steel	WLT, hardness	Electrode material	Copper electrode produced thicker and harder WL as compared to graphite electrode.
2001	Lee and Li [60]	Tungsten Carbide(WC)	MRR and surface roughness	Copper, graphite and Copper-Tungsten(CuW) as electrode	Graphite gives highest values of MRR and SR followed by CuW and Cu respectively
2004	Singh et al. [61]	tool steel En-31	MRR	Cu, CuW, brass and aluminum as electrode material	Cu tool electrode resulted in highest MRR followed by Brass, CuW and Aluminum electrodes respectively
2008	Haron et al. [62]	XW42 tool steel	MRR, Electrode wear rate	Copper and Tungsten electrodes	Cu electrode has less wear rate and greater MRR but lower surface finish
2008	Payal et al. [63]	EN 31 tool steel	MRR and surface roughness	Copper, brass and graphite electrodes	Copper electrode gives better MRR as compared to brass and graphite electrodes, whereas brass gives better surface finish
2001	Haron et al. [64]	Tool steel	MRR and tool wear rate	Size of electrode	Low current is suitable for small diameter electrode.
2008	Kojima et al. [65]	General	MRR and Surface finish	Gape width	Arc plasma diameter increased with increasing gap
2010	Yoo et al. [66]	General	MRR and TWR	Gap voltage	Tool wear ratio decreases with increase of voltage
2011	Gostimirovic et al. [67]	Magnesium-Vanadium tool steel	MRR and surface roughness	Pulse duration and current density	Pulse duration has more effect on surface roughness as compared to pulse current.
2004	Hasçalýk et al. [20]	AISI D5 tool steel	Surface roughness	Electrical parameters	SR is directly proportional to the pulse duration and open circuit voltage
2007	Kiyak et al. [68]	AISI P20 tool steel	Surface roughness	Electrical parameters	Low values of pulse current and on-time and high value of pulse off-time generate finer surface finish
2005	Keskin et al. [69]	Steel alloy	Surface roughness	Electrical parameters	Surface roughness has an increasing trend with an increase in the discharge duration.
2000	Rebelo et al. [70]	Copper-Beryllium alloy and steel	Surface roughness and MRR	Electrical parameters	For same energy settings, MRR is ten times smaller and SR is two time smaller for copper Beryllium alloys as compared to steel

Year	Authors	Material	Response variables	Influencing parameters	Remarks
2007	Guu et al. [71]	Manganese–Zinc Ferrite Magnetic Material	MRR, WLT and surface roughness	Electrical parameters	Surface characteristics are not uniform
2001	Guu and Hocheng [72]	Steel alloy	MRR and TWR	Work-piece rotation	Rotation speed of the tool electrode influences MRR and surface roughness
2001	Lee and Li [60]	Tungsten carbide	Surface characteristics	Flushing pressure	There are optimum parameters for precision machining.
2012	Pradhan [73]	AISI D2 tool steel	Surface roughness, crack density and WLT	Electrical parameters	Pulse duration is most effective parameter followed by duty factor, current and voltage

material after each discharge causes residual stresses of tensile nature. These stresses can produce surface cracks if their amount exceeds the rupture strength of the material. These stresses are harmful even if they are much smaller than this strength as they promote early cracking when the material is subjected to repeated loads.

Surface cracks are present on the electric discharge machined surface that extends to the bottom of white layer. But in rare cases, surface crack penetrates the parent material. Surface crack density is more dependent on pulse on-time as compared to pulse current. Presence of such cracks causes early failure of components as crack initiation life is lost.

High material removal rate (MRR) is generally achieved at the cost of surface deterioration but surface treatments after EDM can improve the values of both MRR and surface integrity. Currently, efforts are being made to improve the MRR and machining accuracy by introducing conductive powder in dialectic liquid to increase the inter-electrode gap during EDM. Ultrasonic waves are used to improve the cleaning of the removed debris from the gap. Magnetic field assisted EDM have been considered to improve the machining rate and surface characteristics of the material. There are many factors that can influence the material properties independently; therefore, there is still a room for future research to explore the effects of different parameters on recently investigated hard and conductive materials. Development of smaller diameter wires with advanced material properties to handle small work pieces is a challenge for future manufacturers. The development of economical electrodes with high conductivity and elevated fracture toughness for high material removal rate and high cutting speed will remain a key research area. Rare studies have been performed on the machining of ceramics like Al_2O_3 and ZrO_2 by using assisting electrodes to expedite sparking of more electrically resistive materials. More investigations are needed to understand the machining process using work-piece rotation and tool vibrations.

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